Wear Particle Analysis Results for Variably Loaded Single Reduction Helical Gearboxes

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Abstract: The Mechanical Diagnostic Test Bed (MDTB) was constructed as a multi-sensor instrumented gear/transmission test stand by the Pennsylvania State University in the area of Condition-Based Maintenance (CBM). The MDTB data acquisition system is capable of recording (using PC-LabWindows) transitional run-to-failure data sets from a variety of commensurate and non-commensurate (vibration, oil, temperature, and acoustic emission) sensors. Off-line JOAP oil analysis results (ferrography) for samples collected from industrial grade (off-the-shelf) single-pair helical gearboxes subjected to sustained output loads of 2-3 times their rated maximum torque are presented.

The off-line oil ferrography results indicated a much higher sliding and cutting wear particle content for the higher loaded (3X maximum torque) experiments. This agrees with intuition. One of the goals of this research is to fuse oil sensor information on lubricant condition in an on-line manner with vibration (accelerometer) data as well as with acoustic emission and thermographic sensor data in order to effectively detect developing or incipient faults, and to predict (with confidence bounds) the remaining useful life of the system (gearbox).

Keywords: Condition monitoring; helical gears; transitional data; ferrography; fusion; MDTB; lubricant condition.

Introduction: One of the principal goals of CBM is the development of the capability to accurately predict remaining useful life of a critical component or system without interrupting operational time for inspections. A successful integration of this kind of (CBM) technology within an overall maintenance program promises to result in increased cost savings, machine usage, and human safety. At this point, the benefits of oil analysis for condition monitoring have been well-documented [2] and need not be repeated here.

Motivation for the Mechanical Diagnostics Test Bed (MDTB): Methods in maintenance technology are constantly evolving. A multitude of new technologies has been applied to the maintenance and mechanical diagnostics problem. Examples include advanced detection methods for temperature, oil analysis, and vibration signals. A limiting factor in the further development of CBM has been a lack of high-fidelity data of faults as they initiate and evolve. This shortcoming is addressed by the MDTB effort to provide a realistic test stand that effectively represents an operational environment while bridging the chasm between typical university-scale test facilities and industrial-scale applications. The MDTB directly accommodates the need for transitional data that tracks faults from initiation to an ultimate failure mode by including oil analysis.

MDTB Description - General Overview: The MDTB, shown in Figure 1 below, is functionally a motor-drivetrain-generator test stand. The gearbox is driven by a 30 Hp AC (driver) motor, while torque is applied by a 75 Hp AC (absorption) motor. The system speed and torque set points are produced by analog input signals supplied by the Data Acquisition Computer. Shafts are connected with tandem flexible and rigid couplings. Torque-limiting shear couples are used on both sides of the gearbox to prevent transmission of excessive torque as could occur with gear jam or bearing seizure. Furthermore, torque cells are used on both sides of the gearbox to directly monitor efficiency and the loads transmitted. The MDTB has the capability of testing single and double reduction industrial gearboxes with ratios from about 1.2:1 to 6:1, and are nominally in the 5-20 Hp range.

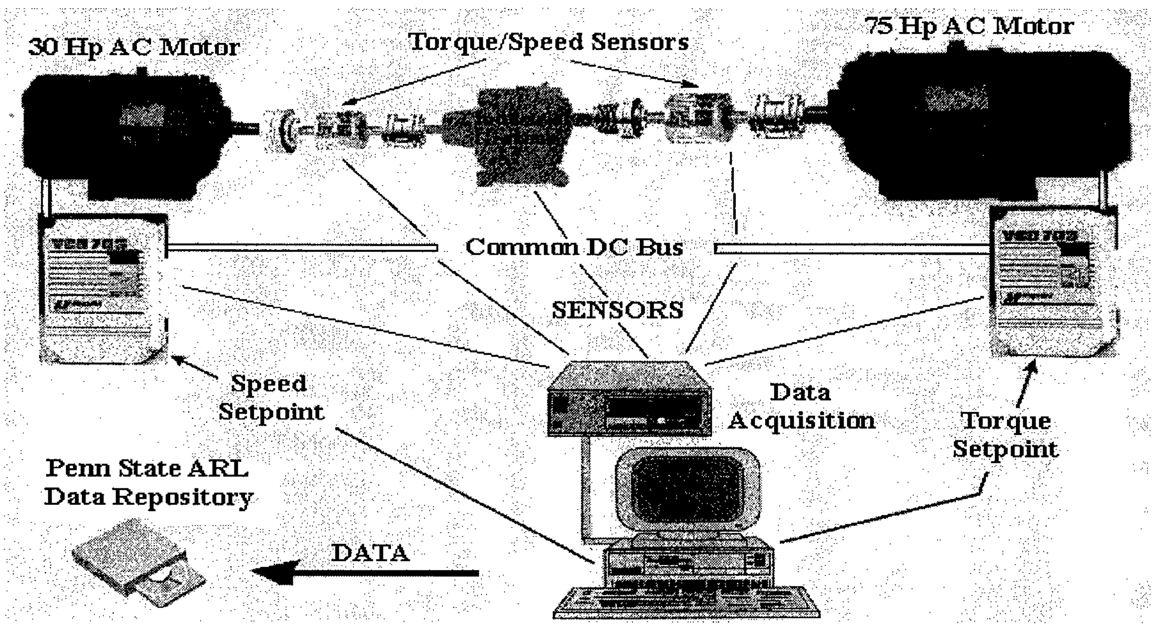

Figure 1. Mechanical Diagnostics Test Bed

Status: Ten gearboxes have been run to failure on the MDTB. These were all single reduction 10 Hp industrial gearboxes. They contain a single pair of helical gears with a gear ratio of 1.5:1, i.e., 30-tooth pinion / 46-tooth output gear, with ball bearings on the input shaft and tapered roller bearings on the output shaft.

The first run was primarily a shakedown run resulting in a tooth breakage failure from first running the gearbox at twice its rated torque for ten days and three times its rated torque for an additional eleven hours. The final result was a complete decoupling of input and output shafts due to severe tooth breakage.

The second through sixth gearboxes were all run under the same load conditions. Each was first run at its rated speed and torque for four days (break-in period), and then loaded to three times its rated torque at rated speed until failure. The point of failure was established as at least two accelerometers exceeding 150% of their nominal RMS vibration level. In all five cases, the final result was tooth breakage. The seventh through tenth gearboxes were run in the same manner, except that after the break-in period they were loaded to twice their rated torque. Figure 2 shows the total overload period run times for the nine gearboxes.

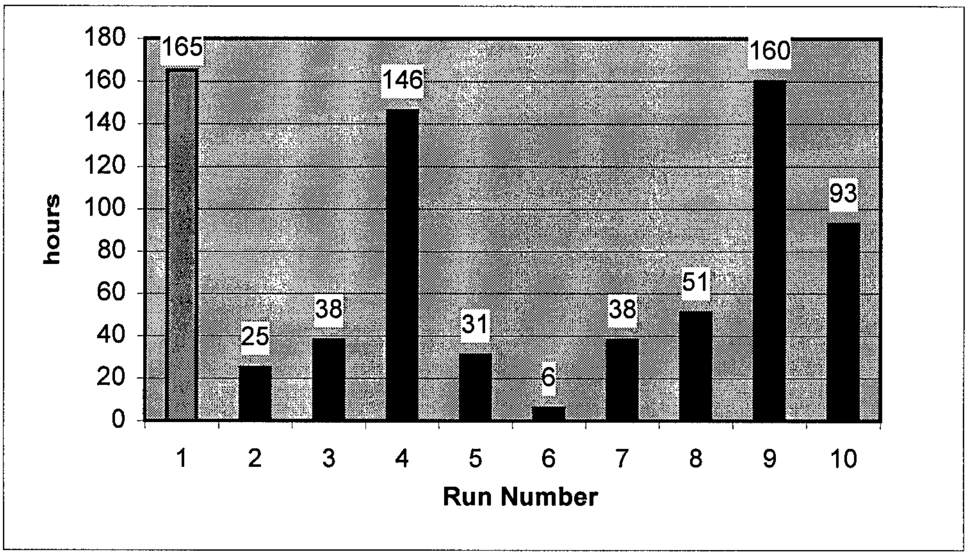

Figure 2. Loaded Gearbox Run Time

The mean (μ) and sample standard deviations (s) in hours on load for runs 2-6 (3X output torque load) and runs 7-10 (2X output torque load) were ($\mu = 49.2$, $s = 55.4$) and ($\mu = 85.5$, $s = 54.9$), respectively. Note that lower output torque loading (runs 7-10 above in Fig. 2) results in longer time-to-failure on average. This agrees with intuition. However, the variance in run times is relatively high and approximately equal for both load conditions. It is a coincidence that the third run of each set (#4 vs. #9) has the longest

time-to-failure for each set. One can not draw statistically significant conclusions from this data – which is presented here, but is used to illustrate the approach on which we are embarking.

Oil Sampling and Analysis: After MDTB shutdown and suspected gear-tooth failure, approximately 8 oz of the lubricant (oil type Mobile SHC 634) is collected as soon as possible from the gearbox well and mailed to the Joint Oil Analysis Program (JOAP) for analysis. At the beginning of these experiments, a clean test sample of the same oil was submitted to the JOAP to serve as a baseline sample. Tables 1 and 2 below represent both the post-mortem gearbox damage autopsy and ferrography results to date.

The Direct Reading Ferrography (DRF) procedure carried out measures the amount of magnetic particle wear debris from the sample, evaluating it with respect to typical ferrographic wear particles based on type, size and quantity.

	3X Loading					2X Loading		
Part	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
Drive Gear	Tooth Failures	Tooth Failures	Tooth Failures	Tooth Failures	Tooth Failures	Tooth Failures	Tooth Failures	Tooth Failures
Input Ball Bearings	Scoring Pitting	Scoring	Scoring	Scoring	Scoring	Scoring	Scoring	Scoring
Output Roller Bearings	Scoring	Scoring	Scoring	Scoring	Scoring Damaged Inner Race	Scoring	Scoring	Scoring

Table I. Autopsy of MDTB Gearboxes

	3X Loading					2X Loading		
DR Ferrography	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
Rubbing Wear (rdn)	4	3	4	4	4	4	4	4
Sliding Wear (rdn) Size (microns)	3 50	3 70	4	4 120	4 120	4 40	3 80	3 90
Cutting Wear (rdn) Size (microns)				2 60		3 10		
Laminar Wear (rdn) Size (microns)	3 62	3 70	4 130					
Black Oxides (rdn)		3			3	4	3	3

Table II. Direct Reading Ferrography

Table I lists the observed post-mortem faults for the gearbox in question for each run. Essentially, Table 1 is self-explanatory. Tooth failure here means at least one (and usually two side-by-side) broken gear-teeth. The contact ratio for the helical gears in the experiment was approximately 2.1.

Table II lists the DRF results in relative units specific to the JOAP Laboratory. For example, in the row labeled "sliding wear," the numbers 3 and 4 are so-called "rdn" or relative density values. These numbers range from 0 – 4, with 0 = no particle and 4 = maximum level for the given equipment. The rdn ranges may be different from lab to lab. Some labs use a 0 – 10 scale. The remaining lower numbers such as 50, 70, 120, etc., (where provided) indicate the size (in microns) of the particles observed.

For Run #4, the gearbox lasted 146 hrs (Figure 2) while operating under a 3Xs maximum output torque condition. After failure the gearbox was disassembled and two broken gear teeth were seen as well scoring on both input ball and output roller bearings (Table I). Oil analysis indicated large quantities for particles resulting from Rubbing Wear, Sliding Wear, and Laminar Wear (Table II).

As expected, indicators for rubbing wear and sliding wear occurred in every case. Rubbing wear is a universal manifestation of normal operational degradation in mechanical systems, and is indicated by the presence of wear particles smaller than 15 mm in the major dimension. Sliding wear occurs whenever mechanical systems are operated beyond their normal load and/or speed envelope, as we did in our testing; it is indicated by the presence of flat, coarse, striated platelets exceeding 20 mm in their major dimension.

Each of the various paths to failure passed through at least one of three observable alarm conditions (our term for conditions indicating a high risk of imminent failure): cutting wear, laminar wear, or deficient lubrication. Cutting wear, which arises from misalignment or the presence of solid contaminants in the lubricant, is indicated by swarf-like particles 2-5 mm wide and over 100 mm long [2]. Laminar wear results from rolling contact failure of bearing and gears and is indicated by non-striated platelets of various sizes. Deficient lubrication results from poor design or excessive loading or speeding, and is indicated by the presence of black oxide in the lubricating oil.

Figure 3 (next page) includes run number labels along each path segment. In every case of 2X loading black oxides (indicator for insufficient lubrication) appears in the lubricant prior to breakdown.

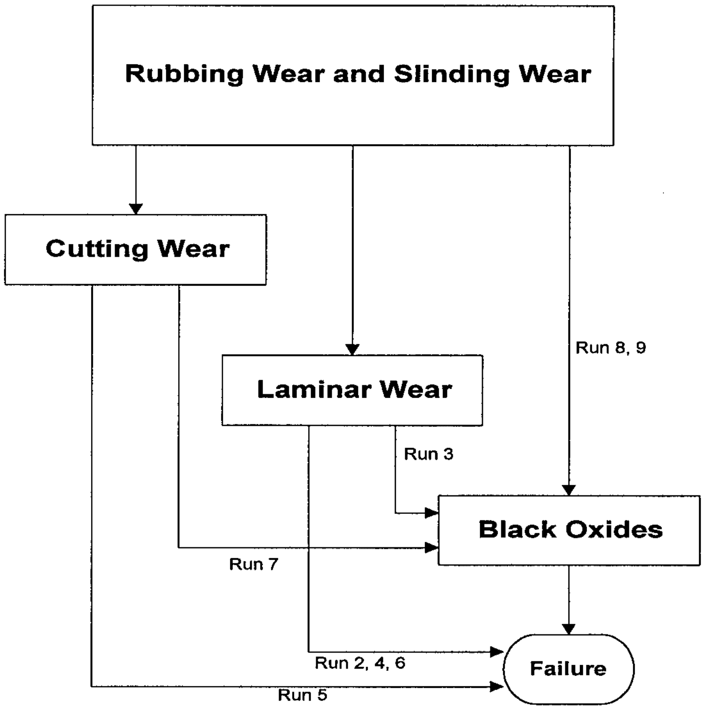

Figure 3. Paths to Failure

All but one case of 3X loading indicators from laminar wear are present; on the other hand only one of these cases showed black oxide observed in the oil sample. While eight samples are hardly enough for valid statistics, these observations suggest that correlating changes in ferrographic content of lubricating oil with operating parameters (e.g. loading level) will facilitate in-line degradation analysis. (As of this writing, oil analysis results for Run #10 have not been finished.) This illustrates the approach on which we are embarking to develop a real-time condition monitoring capability.

Examples of cutting and sliding wear are exhibited in Figures 4 and 5 below, [5].

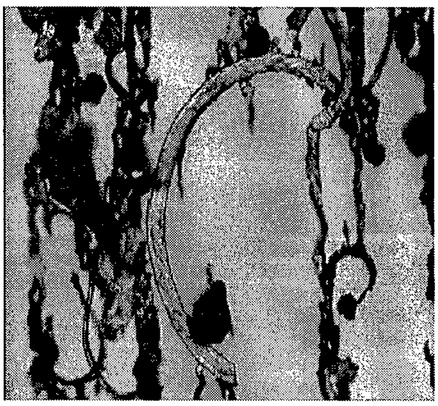

Figure 4. Cutting Wear

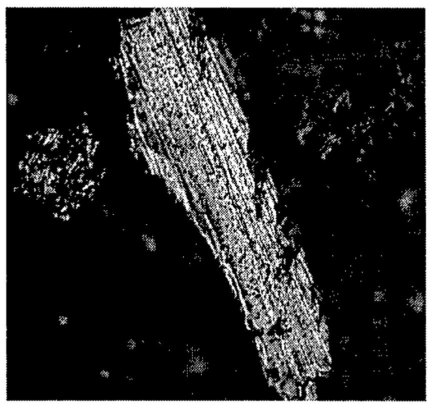

Figure 5. Sliding Wear

Summary & Conclusion: A testbed setup (MDTB) for researching machine component failure detection, diagnosis, and prediction using a medium grade quality off-the-shelf gearbox has been described. Furthermore, wear particle oil lubricant ferrography results as processed by the JOAP have also been presented.

High rdn values (figure of merit) indicated primarily rubbing, sliding, and laminar wear. Cutting wear seemed absent or was not reported in many cases. Oddly, Run #4 had the maximum allowable rdn reading in 3 out of 4 wear categories, but lasted the longest time on load at 146 hrs. Thus, to a large extent correlation between run times in Figure 2 and wear analysis in Table II is somewhat inconclusive. Sampling at the end of each run only yields the final figures of merit for the condition of oil debris contamination, but is not sufficient for tracking or predicting failure along the way. For this we need to sample more often per run.

To accomplish this an on-line dielectric-based oil condition monitor has been installed on the MDTB. Other on-line oil monitoring sensors are also under consideration. In a future paper, we shall report the results and performance of these on-line continuous oil condition sensors as well as their overall predictive diagnostic effectiveness when fusing with other sensor data types such as vibration.

References:

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[5] "Typical Ferrographic Wear Particles", poster pictures provided by Predict Technologies Division, Cleveland, OH.